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FLOW FIELD MEASUREMENTS OF A JET IN CROSSFLOW WITH A LASER VELOCIMETER

T. W. Binion, Jr.

ARO, Inc.

November 1971

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FOREWORD

The test reported herein was sponsored by the Air Force Flight Dynamics Laboratory (AFFDL), Air Force Systems Command (AFSC), under Program Element 62201F, Project 8219, Task 07.

Results of the test were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract F40600-72-C-0003. The test was conducted from June 7 to June 16, 1971, under ARO Project PD0141, and the manuscript was submitted for publication on August 19, 1971.

This technical report has been reviewed and is approved.

George F. Garey	Duncan W. Rabey, Jr.
Lt Colonel, USAF	Colonel, USAF
AF Representative, PWT	Director of Test
Directorate of Test	

ABSTRACT

Tests were conducted in the Low Speed Wind Tunnel (V/STOL) to measure the velocity field of a jet issuing from a flat plate with crossflow. Velocity components were measured with a dual-scatter laser velocimeter at effective velocity ratios of 0.125 and 0.250. The data yielded velocity vectors along lines normal to the jet centerline in three planes parallel to the plane of symmetry. Indications of the flow field turbulence were also measured.

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NOMENCLATURE

D	Nozzle exit diameter, 1.06 in.
p	Pressure, psfa
r	Nozzle exit radius, in.
V	Flow field velocity, ft/sec
V_e	Effective velocity ratio, $(V_\infty/V_j)\sqrt{\rho_\infty/\rho_j}$, ft/sec
x	Axial position, positive downstream from the nozzle center-line, in.
y	Lateral position from the plane of symmetry, positive to the right looking upstream, in.
z	Vertical position from the nozzle exit plane positive out of the nozzle, in.
ρ	Density, lb/ft^3

SUBSCRIPTS

a, b, c	Measured components, see Fig. 4
j	Jet exit conditions
t	Stagnation conditions
∞	Free-stream conditions

SECTION I
INTRODUCTION

Adequate representation of a jet in crossflow has become an increasingly important problem as the development of V/STOL aircraft continues. The induced flow field produced by direct lift jets during transition flight in many cases produces significant aerodynamic lift losses and large positive pitching moments. Present knowledge of jet induced flow fields allows the aerodynamic effects of jets to be predicted only with a high degree of uncertainty (Ref. 1). The investigation reported herein is part of a broad effort sponsored by the Air Force Flight Dynamics Laboratory (AFFDL/FGC) to increase the understanding of jet flow fields.

The purpose of the present investigation was to measure the velocity field of a jet issuing from a flat plate with crossflow. The data were obtained in the Low Speed Wind Tunnel (V/STOL) of the Propulsion Wind Tunnel Facility (PWT) for the AFFDL/FGC.

The tests were conducted with a constant test section dynamic pressure of 20 psf at two values of the effective velocity ratio, V_e, equal to 0.125 and 0.250. Two-dimensional velocity measurements were obtained in the region of the jet and the jet wake in the plane of symmetry and planes 2- and 4-jet diameters from the symmetry plane. The measurements were obtained with a dual-scatter laser velocimeter.

SECTION II
APPARATUS

2.1 TEST FACILITY

The Low Speed Wind Tunnel (V/STOL) is a continuous flow, closed-circuit, constant-total-pressure wind tunnel in which velocities from 5 to 250 ft/sec can be attained. Flow is generated by a single-stage, fixed pitch fan driven by a 100-hp electric motor through a variable speed magnetic clutch. The test section has a 30- by 45-in. rectangular cross section and is 72 in. long. The horizontal test section walls each contain ten slots which provide an overall test section wall porosity of 2.4 percent. The solid vertical walls are made of 3/8-in.-thick plexiglass. The tunnel was equipped with a ground board 37 in. wide by 56 in. long and located 7 in. below the top wall. A complete description of the tunnel and its operating characteristics may be found in Ref. 2.

2.2 TEST ARTICLE

The test article consisted of a convergent nozzle oriented normal to the ground board as shown in Fig. 1. The test installation is shown in Fig. 2.

The nozzle was constructed from a standard 3- to 1-in.-diam, schedule 40, concentric pipe reducer. The nozzle exit pressure distribution is presented in Fig. 3.

2.3 INSTRUMENTATION

Planar velocity components were measured with a dual-scatter laser velocimeter. The velocimeter (some components of which are indicated in Fig. 2) consists of an argon laser, an optics package, focusing lenses, phototube, and associated electronics. The optics package splits the laser beam into three equal intensity beams. The three beams, which in cross section are at the vertices of an approximately 45-deg right triangle, are converged to a common intersection region by a focusing lens. Since the focusing beams form the edges of a triangular pyramid, it is impossible to position the focal region on the surface of the ground board without one of the beams striking the plate. The minimum distance from the ground board, which is a function of the lens focal length, the beam separation, and the ground board width, was 0.65 nozzle exit diameters.

Since the three laser beams are mutually coherent and identically polarized, each pair will within their intersection region interfere constructively and destructively to produce a set of closely spaced planar interference fringes of alternate bright and dark bands (see Ref. 3). As a scatter center (smoke or dust particle which is assumed to be moving at the local flow field velocity) passes through the beam intersection region, it intercepts the interference fringes, producing a pulsed scattering of light as it passes alternately through the light and dark bands. A collecting lens is used to focus the scattered light through a pinhole onto a photomultiplier tube which produces a pulsed current whose pulsed frequency is directly proportional to the rate at which the particle intercepts the fringes and thus to the flow field velocity. A more complete description of the dual-scatter laser velocimeter principle of operation may be found in Refs. 3 and 4. The period of the photomultiplier tube current pulses was measured by electronic detection equipment. The data represent a probable average velocity within the focal volume formed by the intersection of each pair of beams. The focal volume is defined in Ref. 3 as the $1/e^2$-intensity contours of the

beam intersection region. The installation resulted in an ellipsoidal focal volume with major and minor diameters of 0.26 and 0.003 in., respectively. The velocimeter was mounted on a three-degree-of-freedom traverse mechanism whose travel allowed the focal volume to be placed at any position in one quadrant of the flow field.

2.4 PRECISION OF MEASUREMENT

The data contained in this report were determined from single-sample measurements. While multiple velocity measurements were taken with the velocimeter, the deviation about the mean of each sample is more closely related to the turbulence of the flow than to the precision of the measurement. The uncertainties for the data are estimated from instrument precision and calibration curve-fit deviations and are based on a 95-percent confidence level. The precision of the measurements reported herein are as follows:

V_∞, ft/sec	V, ft/sec	V/V_∞	V_e	x/D, z/D
±0.1	±0.38	±0.003	±0.0003	±0.01

SECTION III
PROCEDURE

Test conditions were established by maintaining a test section dynamic pressure of 20 psf as determined from the tunnel calibration. The jet conditions were established by monitoring the jet total pressure and temperature to obtain an effective velocity ratio, V_e, of 0.125 or 0.250.

The center of the velocimeter focal volume was positioned at discrete points in the flow field with a three-degree-of-freedom traversing mechanism. Data were obtained along lines normal to the jet centerline and also along lines perpendicular to the ground board. The jet centerline location was computed by the empirical equation

$$x/D = V_e^{2.6}(z/D)^3 \tag{1}$$

obtained by Yu. V. Ivanov, reported in Ref. 5.

In order to reject spurious data, the velocimeter automatic readout equipment was designed so that a scatter center must pass through at

least ten interference fringes before a reading is obtained. Thus, if the resultant velocity vector was oriented at an angle greater than about 60 deg to the component being measured, 10 fringes would not be cut and no data would be recorded for that component. The computed resultant, now based on only one component, could be as much as 13 percent low in magnitude with a 30-deg error in direction. Furthermore, in a highly turbulent flow, the data could be heavily biased, depending on the orientation of the average resultant to the components, resulting in an even greater magnitude and directional error.

To improve the data quality, three planar velocity components, indicated in Fig. 4a, were measured instead of the two orthogonal components normally considered. The components were rotated 30 deg from the conventional orientation for convenience during the installation of the velocimeter. Six possible resultant vectors may be computed from the three measured components, depending upon the signs assumed for each component. However, by taking advantage of the orientation limitation, as indicated in Fig. 4b, criteria were established whereby only two vectors (one the negative of the other) are possible. For example, if V_a is zero, the resultant vector must be within 30 deg of the normal to V_a and is thus given by the vector addition of V_b and V_c. It then becomes a relatively simple matter to infer the correct sign of the resultant vector from its flow field position.

Approximately forty measurements were taken of at least two of the components at each flow field position. Under ideal conditions, 40 measurements could be taken in less than fifteen seconds. A component was considered to be zero if the rate of data acquisition was greater than about four times the above rate.

SECTION IV
RESULTS AND DISCUSSION

The planar velocity measurements are presented in terms of a vector velocity field. The tail of each vector is positioned at the spacial location of the measurement. The length and orientation of each vector was determined from the mean value of the measured components. The number accompaning each vector in Fig. 5 is the value of one standard deviation of one of the measured components expressed in percent of the mean value. Because the three components were measured at different times, the deviations computed for resultant vector cannot be directly related to turbulence. Further, since it is impossible to separate the deviation caused by a magnitude change from that caused by a direction

change, the deviations for the resultant vector have no particular value. Thus, the deviation of the component with the largest deviation should be more indicative of the relative velocity fluctuations than the magnitude-direction deviations computed for the resultant vector.

Figure 5 shows the mean velocity field and the percent deviation of each vector in the vicinity of the nozzle exit at y = 0 for V_e = 0.125 and 0.250. Typically, deviations measured in the flow field at y/D of 2 and 4 outside the influence of the jet were between one and two percent. The maximum deviations along any line normal to the jet axis occurred in the the mixing layer, which was to be expected. It can be seen that the deviations within the jet decayed more slowly than the mean values, whereas the deviations in the wake region were essentially constant. Also, there was essentially no difference in the deviations for V_e = 0.125 and 0.250, although the deviations in the wake region were slightly higher at V_e = 0.250. Nevertheless, it would appear to be a reasonable approximation to establish zones wherein the turbulence, hence the Reynolds stress, is proportional to the mean velocity.

The measured planar velocity fields are presented in Figs. 6 and 7 for V_e = 0.125 and 0.250, respectively. In areas where the deviation of the measured components (refer to Fig. 5) was less than ten percent, the three resultant vectors computed from combinations of the three measured components were less than 7 deg apart. However, in areas of high turbulence, the component data are biased because (1) all measurements of a single component were assumed to have the same sign and (2) data below a certain cutoff value (determined by the 10-fringe criteria) were not recorded. The resulting bias affects the direction much more than the magnitude of the resultant. Thus, it is believed that the magnitude of the resultants in high turbulence areas are within ten percent of their true mean values. The direction of the vectors within the jet and particularly within the mixing region is, however, probably subject to modification by as much as 30 deg. The remainder of the data where the maximum deviation was less than about twenty percent are felt to be quite good. The almost vertical vectors in the wake region of the plane of symmetry, Figs. 6a and 7a, were unexpected. Repeated checks, however, attest to the validity of the measurements.

Photographs of oil flow on the surface of the ground plane, Refs. 6 and 7, for example, showed a stagnation point in the plane of symmetry at about x/D = 1.5 with the flow moving in the upstream direction at x/D < 1.5. The stagnation point was caused by the free-stream flow passing around the jet exit and being entrained into the jet. The data shown in Figs. 6a and 7a indicate that the stagnation line was confined

to a region much less than one diameter from the ground plane and that there was a strong up-flow induced as the wake flow was entrained into the jet. In the far field plane of symmetry, Figs. 6a and 7b, the wake flow tended to be parallel to the jet axis rather than the free stream.

At y/D = 2, the effect of the jet was much more pronounced for $V_e = 0.125$ (Fig. 6c) than for $V_e = 0.250$ (Fig. 7c). It is evident in both cases, however, that the line of maximum velocity was bent below the jet centerline axis by the action of the twin vortices which formed as the jet moved downstream (Ref. 5). The plane y/D = 4 was apparently near the edge of the induced vortex at $V_e = 0.125$ (Fig. 6d), as evidenced by the downward velocity component, whereas at $V_e = 0.250$ (Fig. 7d) the presence of the jet was only slightly in evidence.

SECTION V
CONCLUSIONS

The investigation of flow field measurements of a jet in crossflow using a laser velocimeter has resulted in the following conclusions:

1. The maximum turbulence in the measured flow field occurs at the mixing layer between the jet and free stream.
2. It appears to be a reasonable approximation to divide the flow field into regions wherein the turbulence is proportional to the mean velocity.
3. The flow in the wake region shows an essentially constant turbulence and tends to be parallel to the jet axis rather than the free stream.
4. The laser velocimeter in its present state of development produces good results in regions of low turbulence flow. However, the data in high turbulence regions are subject to considerable bias.

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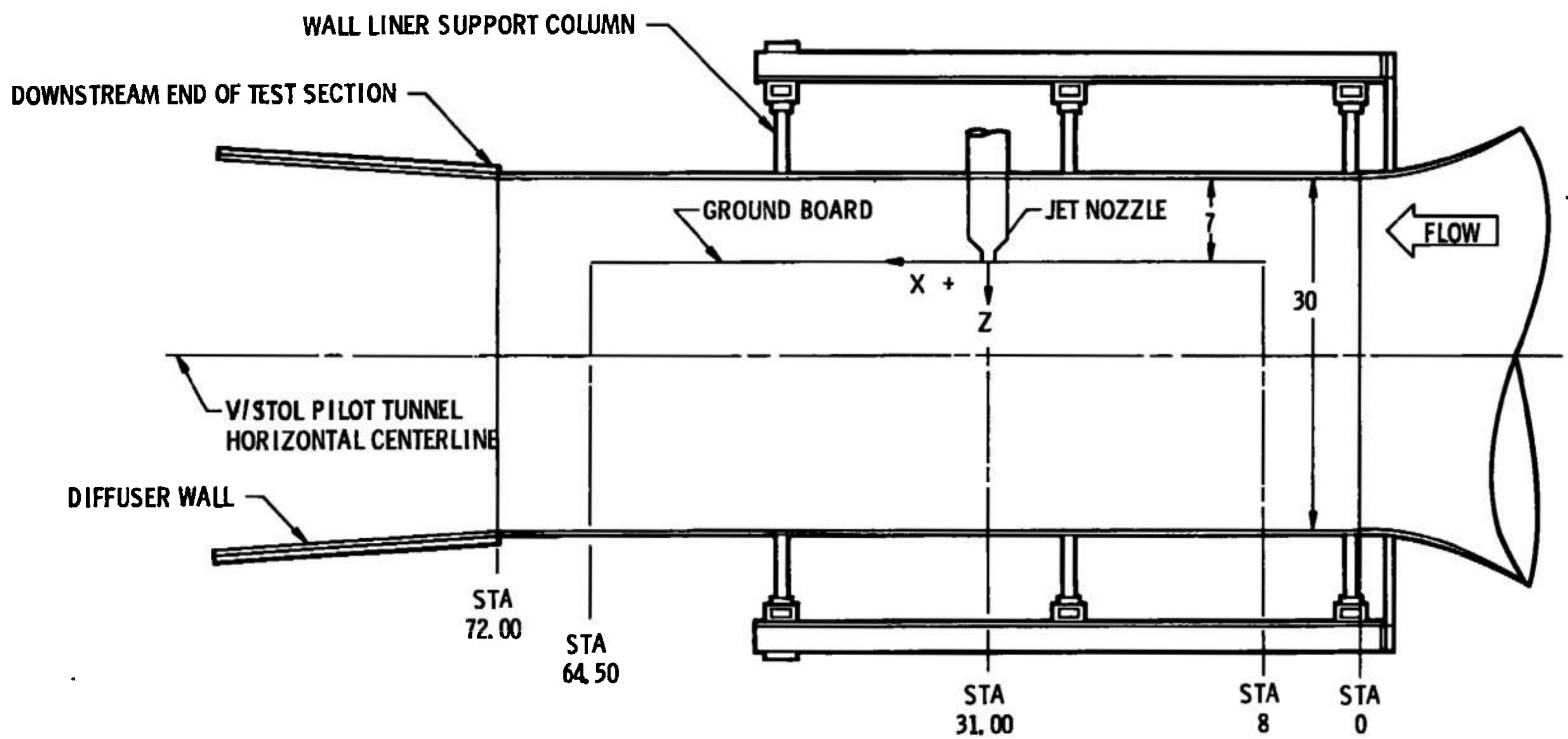
APPENDIX
ILLUSTRATIONS



ALL DIMENSIONS IN INCHES

Fig. 1 Location of the Jet Nozzle in the Test Section

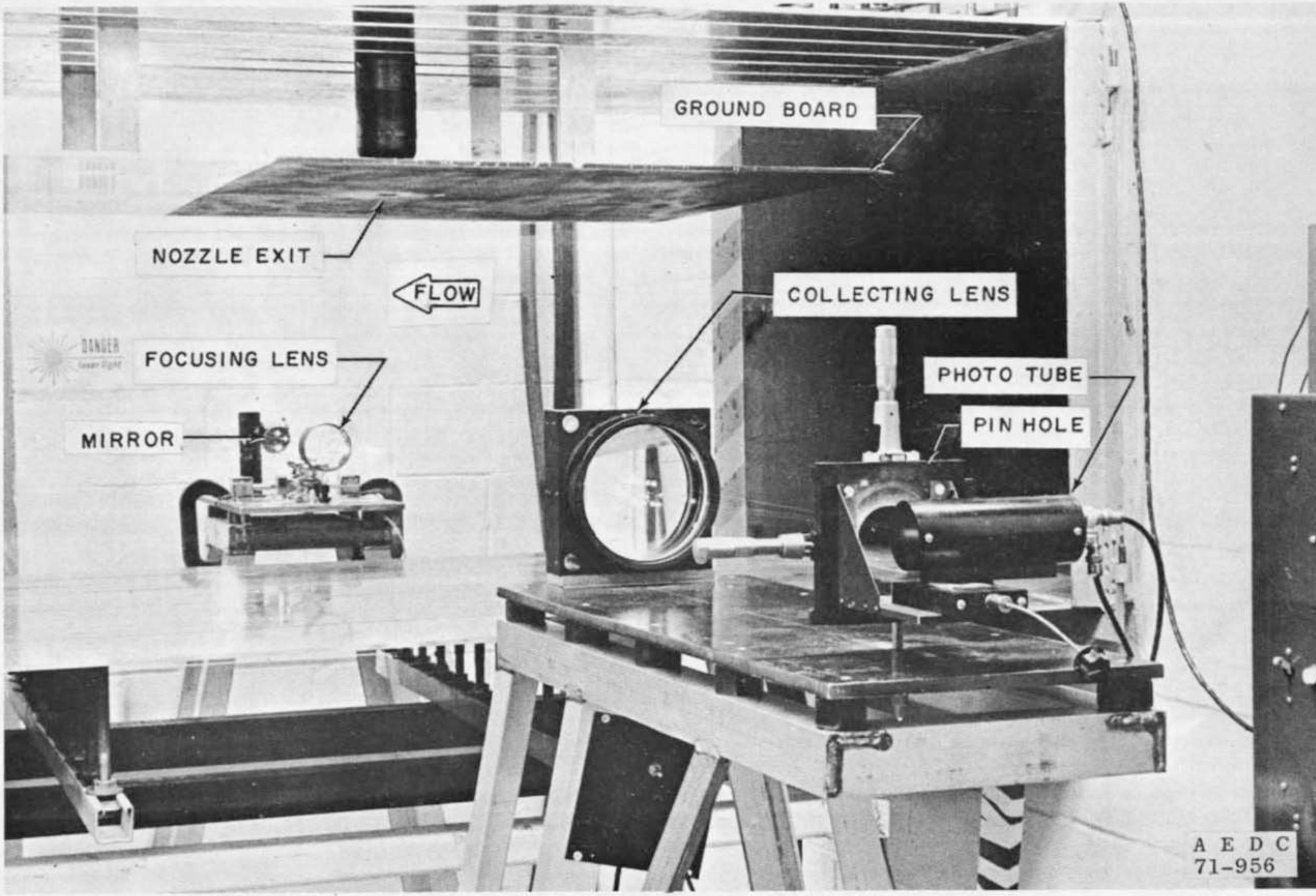


Fig. 2 Test Installation

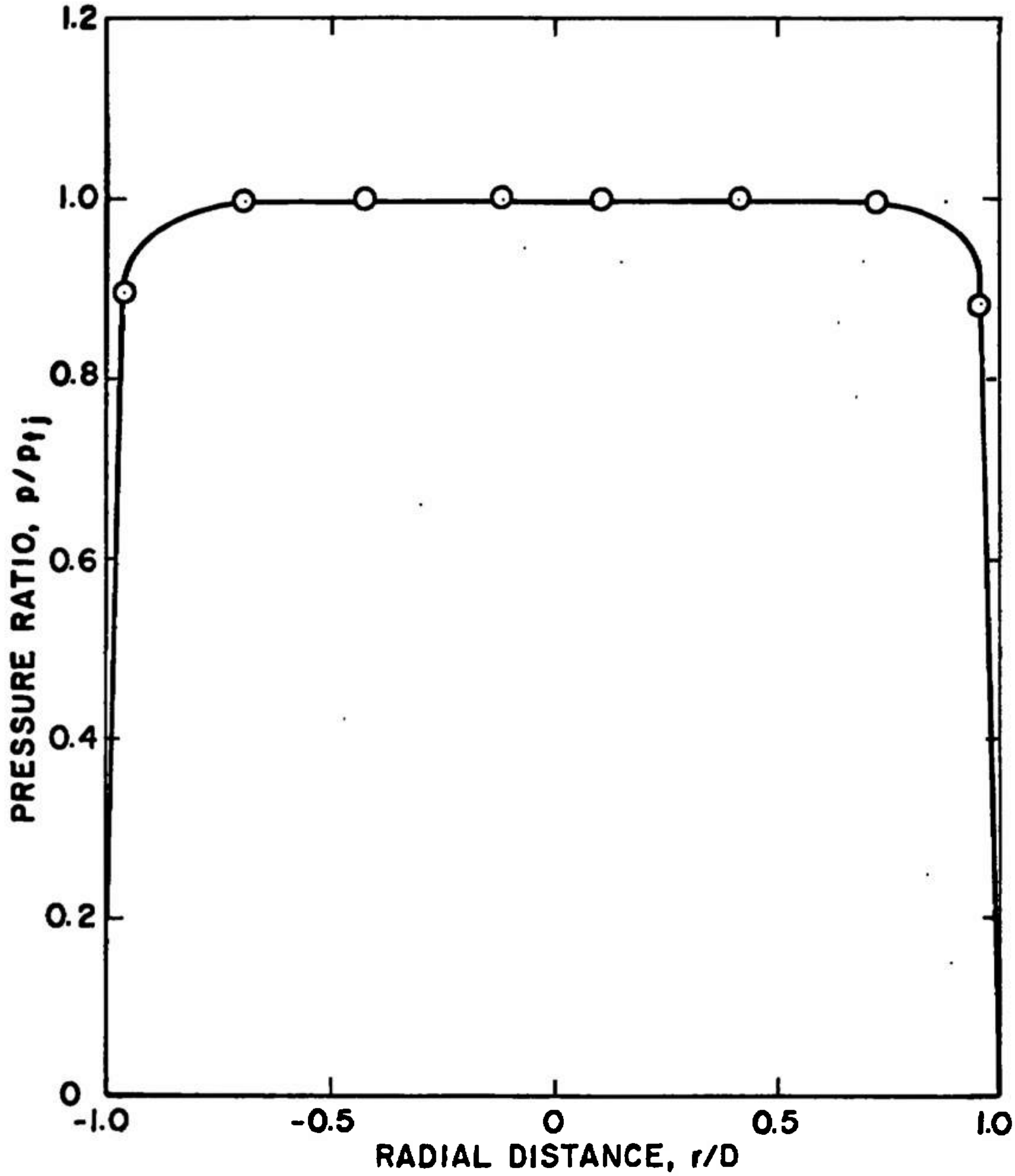
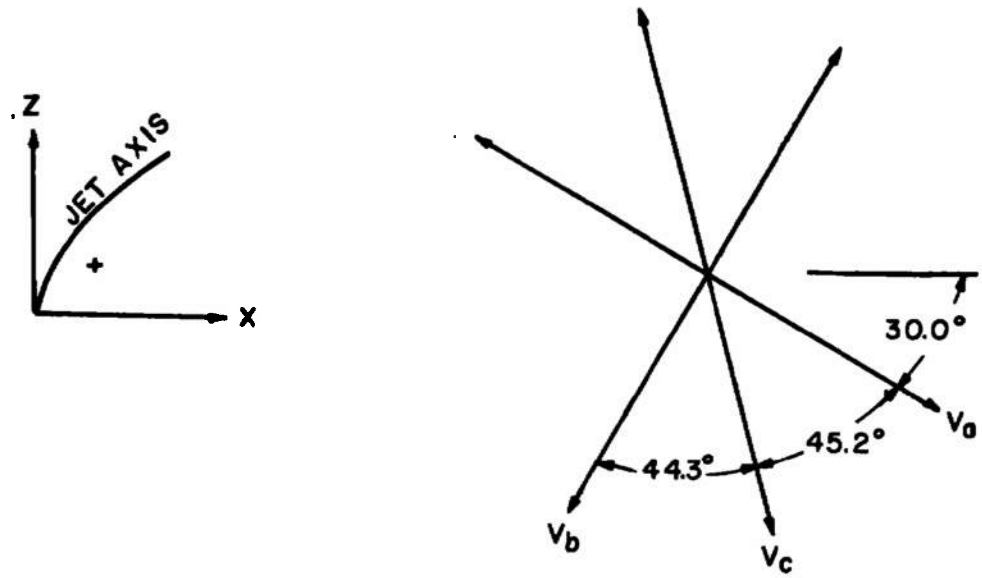
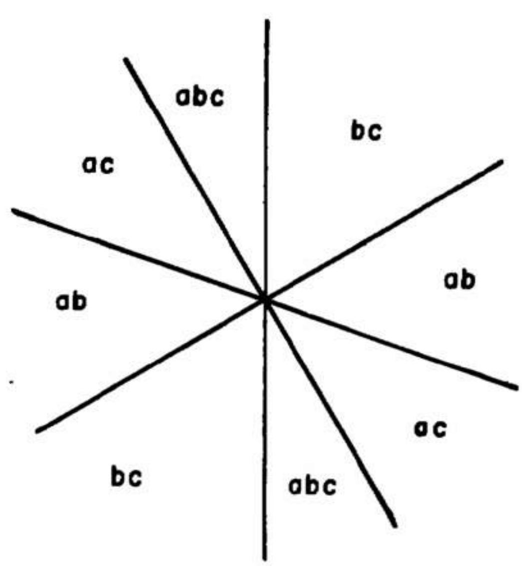


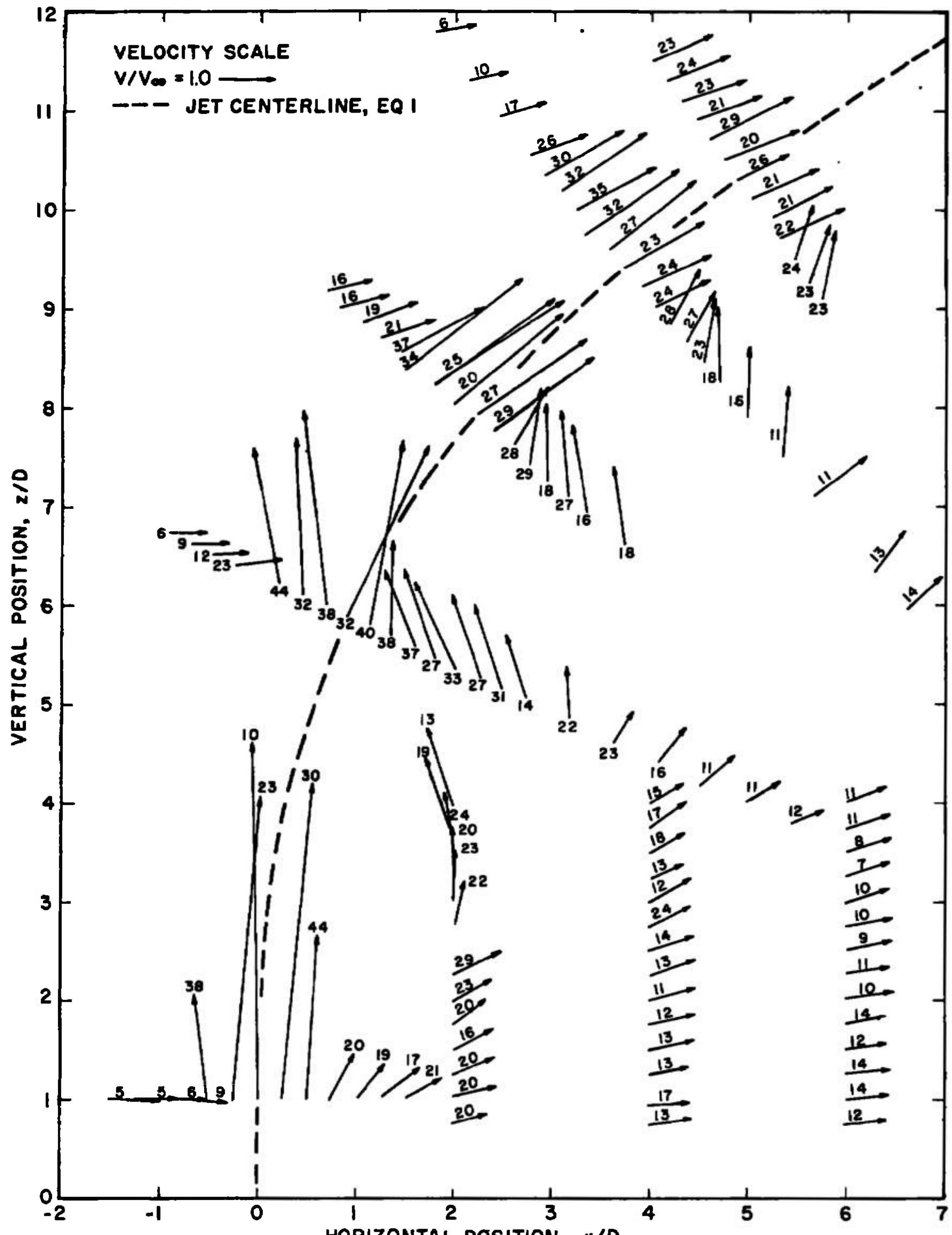
Fig. 3 Nozzle Exit Pressure Distribution



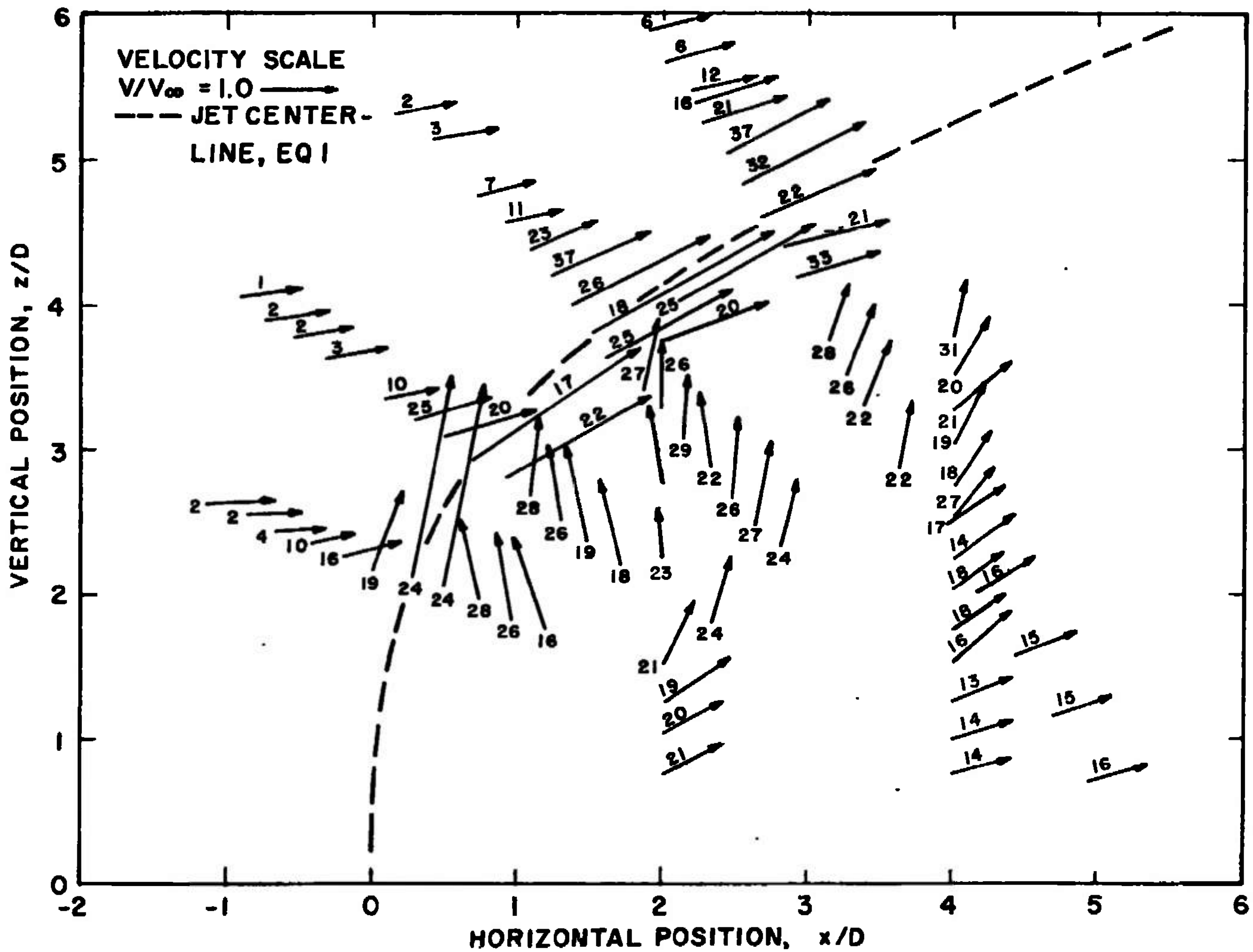
a. Orientation of Measured Velocity Components



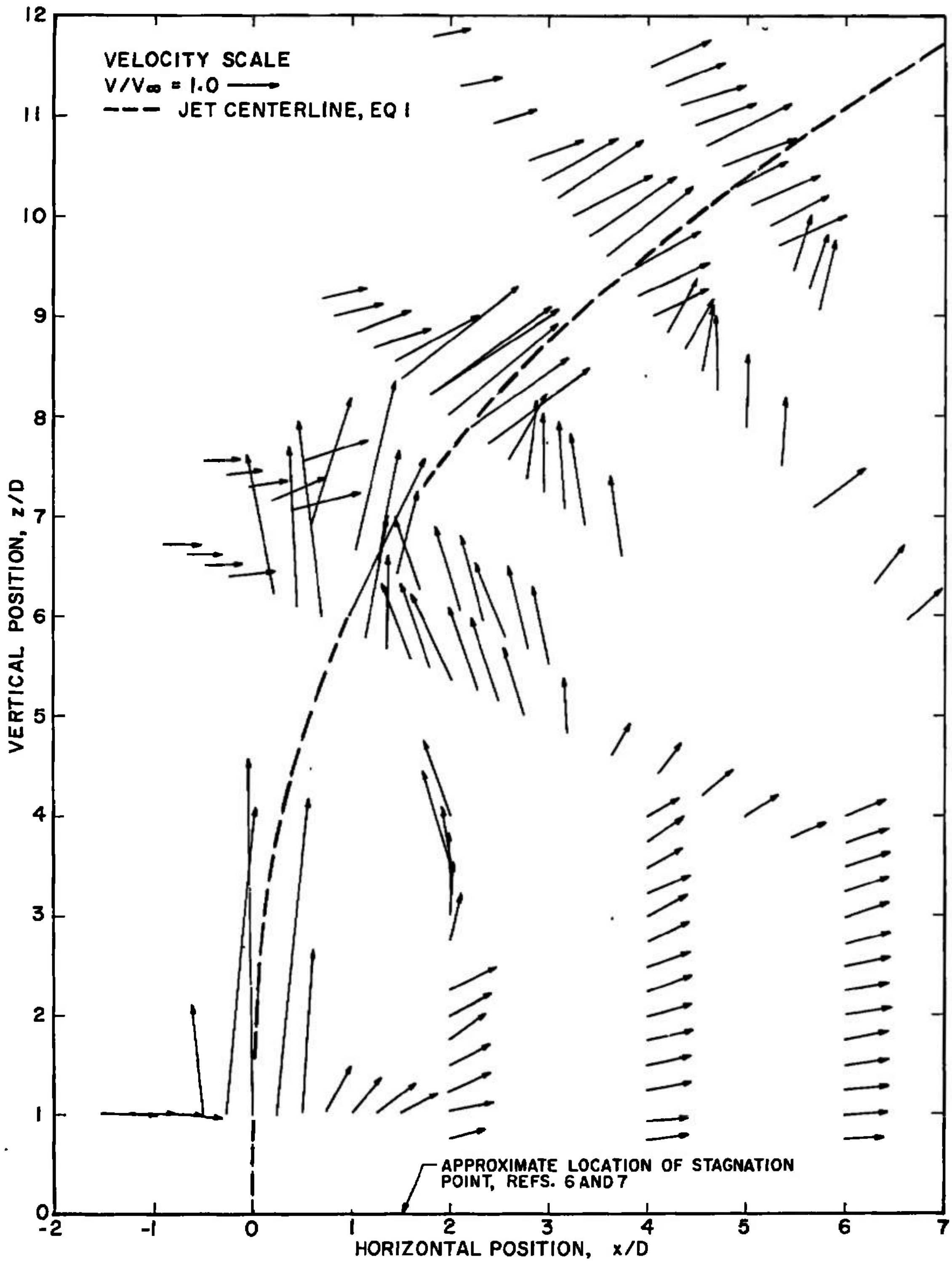
b. Zones of Velocity Component Validity
Fig. 4 Measured Velocity Components



a. V_e = 0.125
Fig. 5 Normalized Standard Deviation of the Velocities in the Vicinity of the Nozzle Exit, y/D = 0

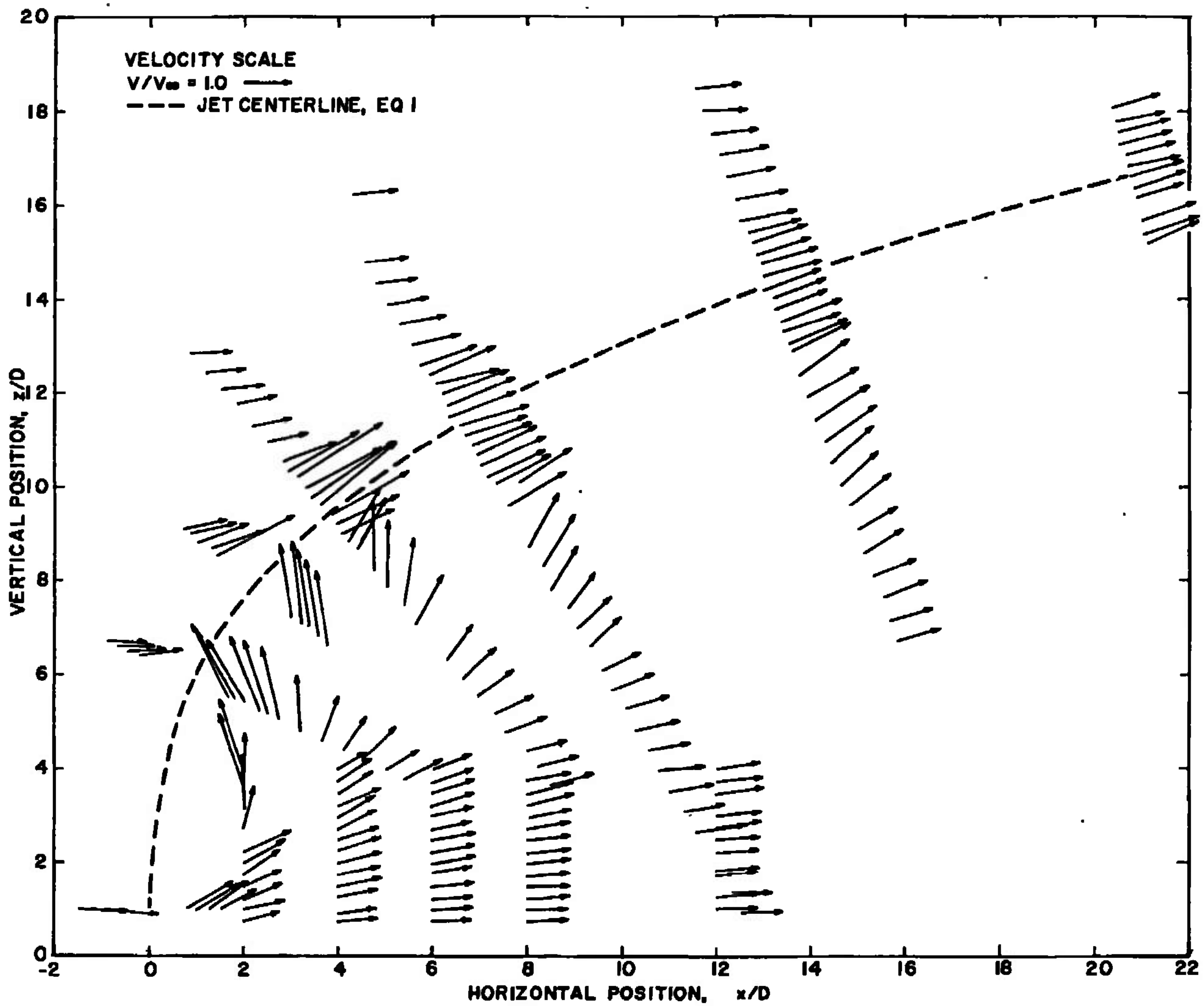


b. V_e = 0.25
Fig. 5 Concluded

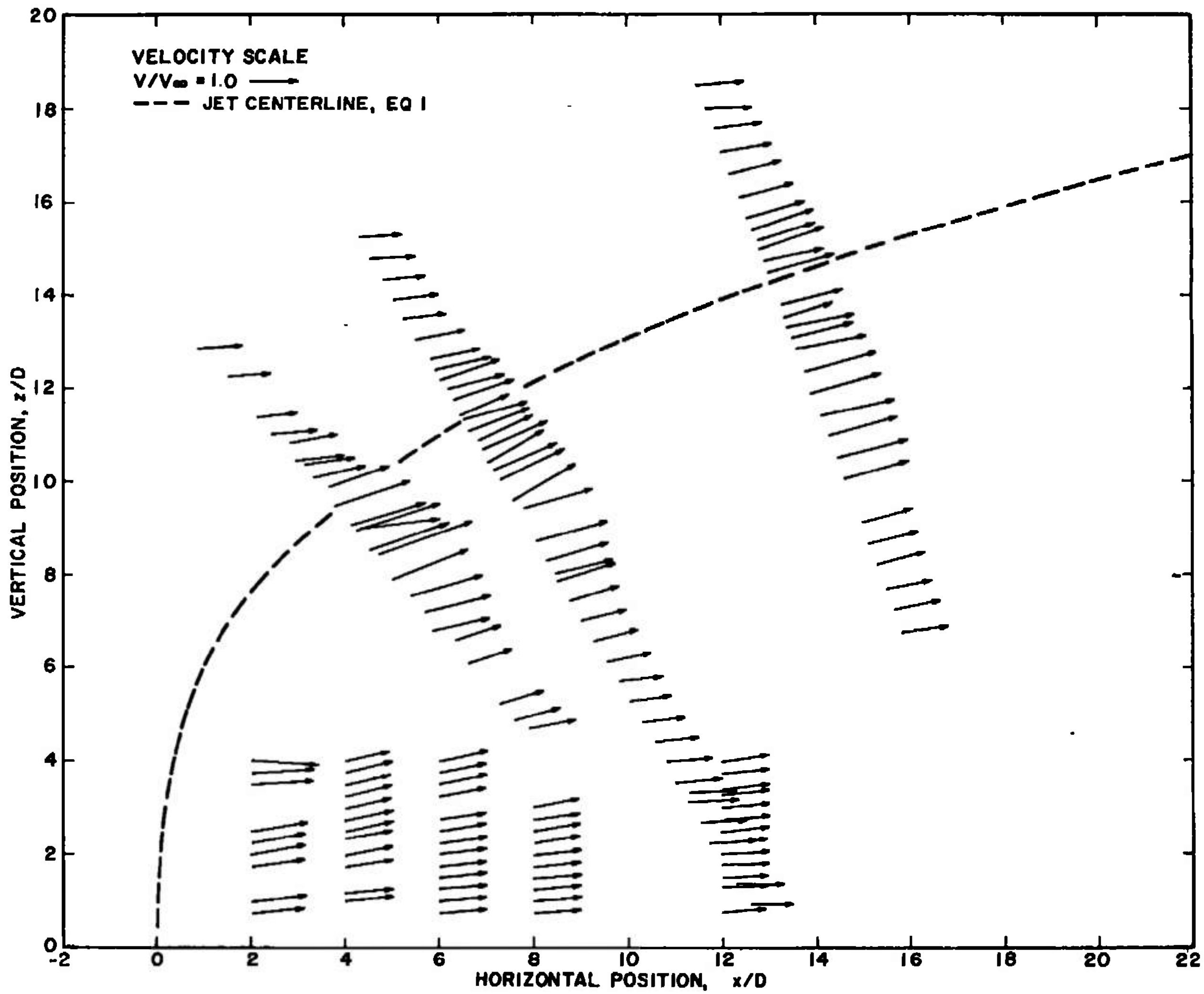


a. y/D = 0, Near Field

Fig. 6 Planar Velocity Field for $V_e = 0.125$

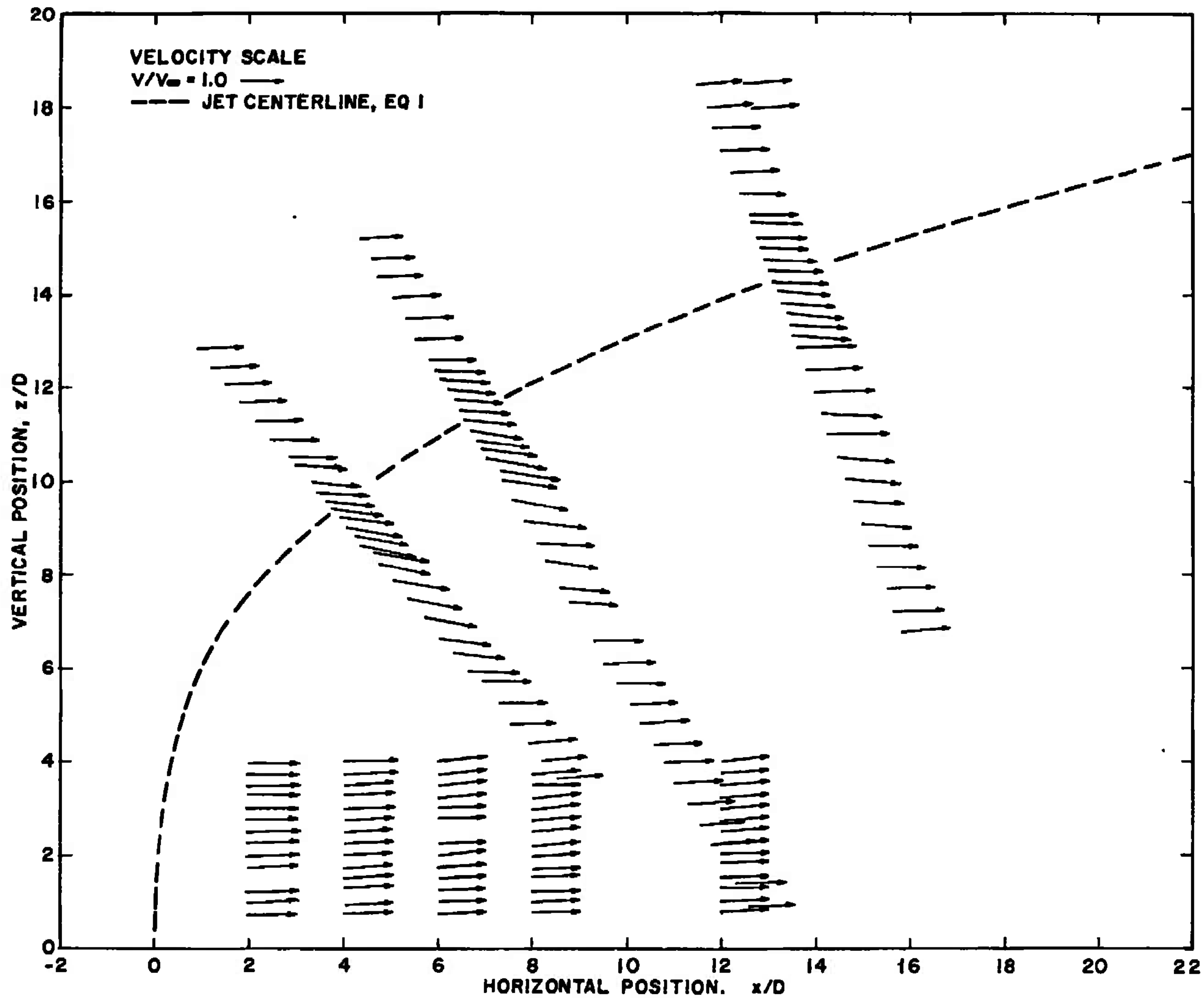


b. y/D = 0, Far Field
Fig. 6 Continued

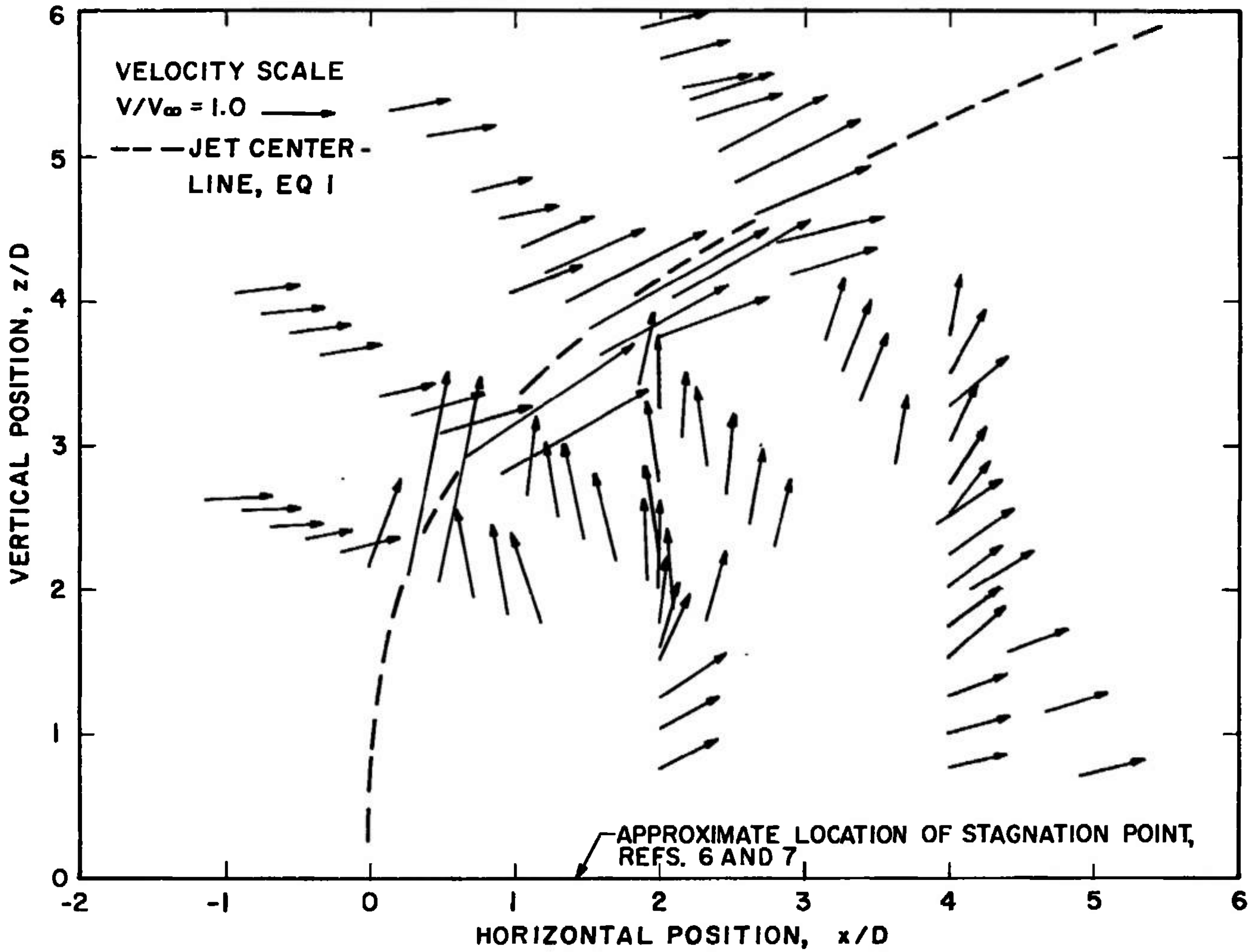


c. y/D = 2

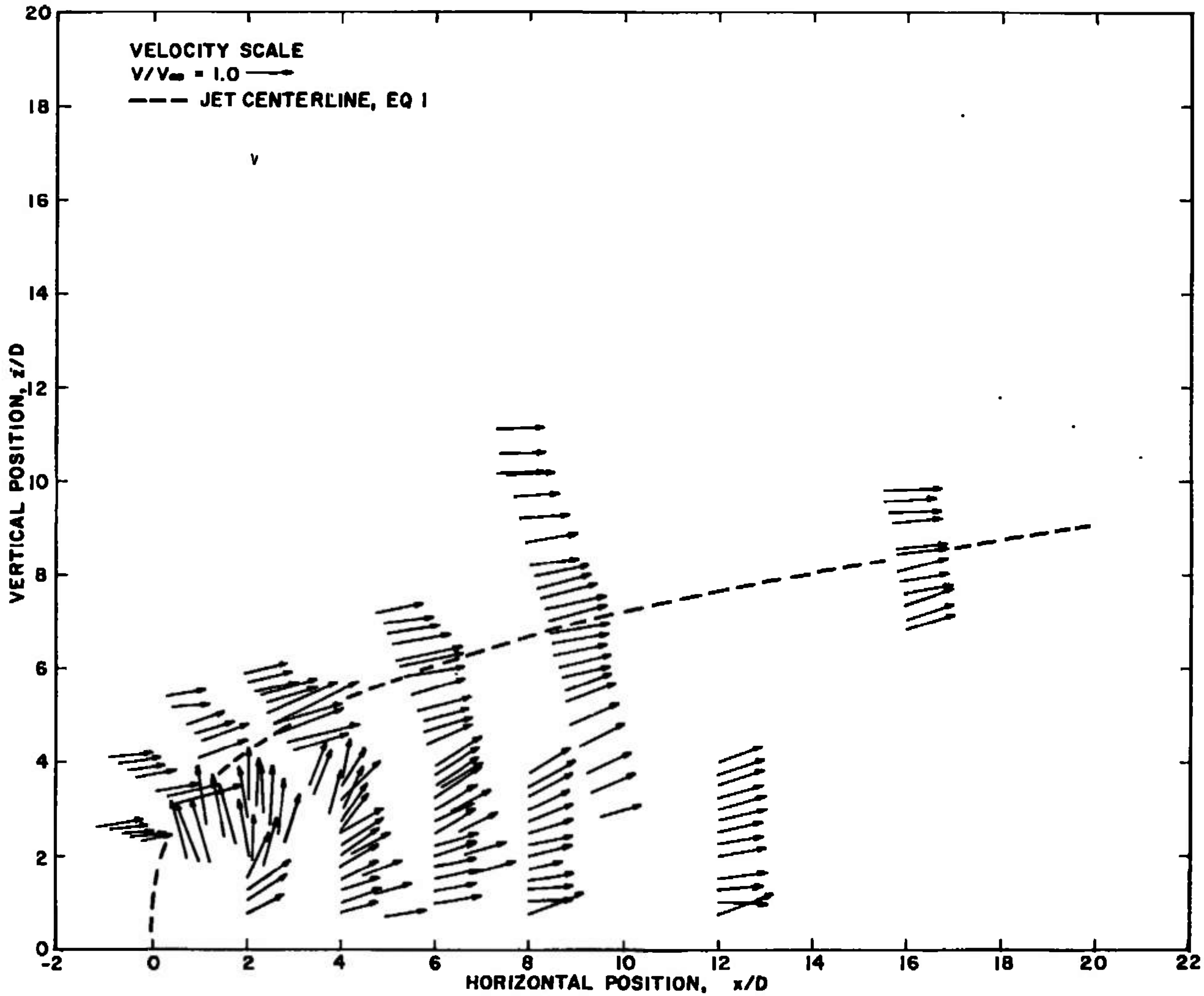
Fig. 6 Continued



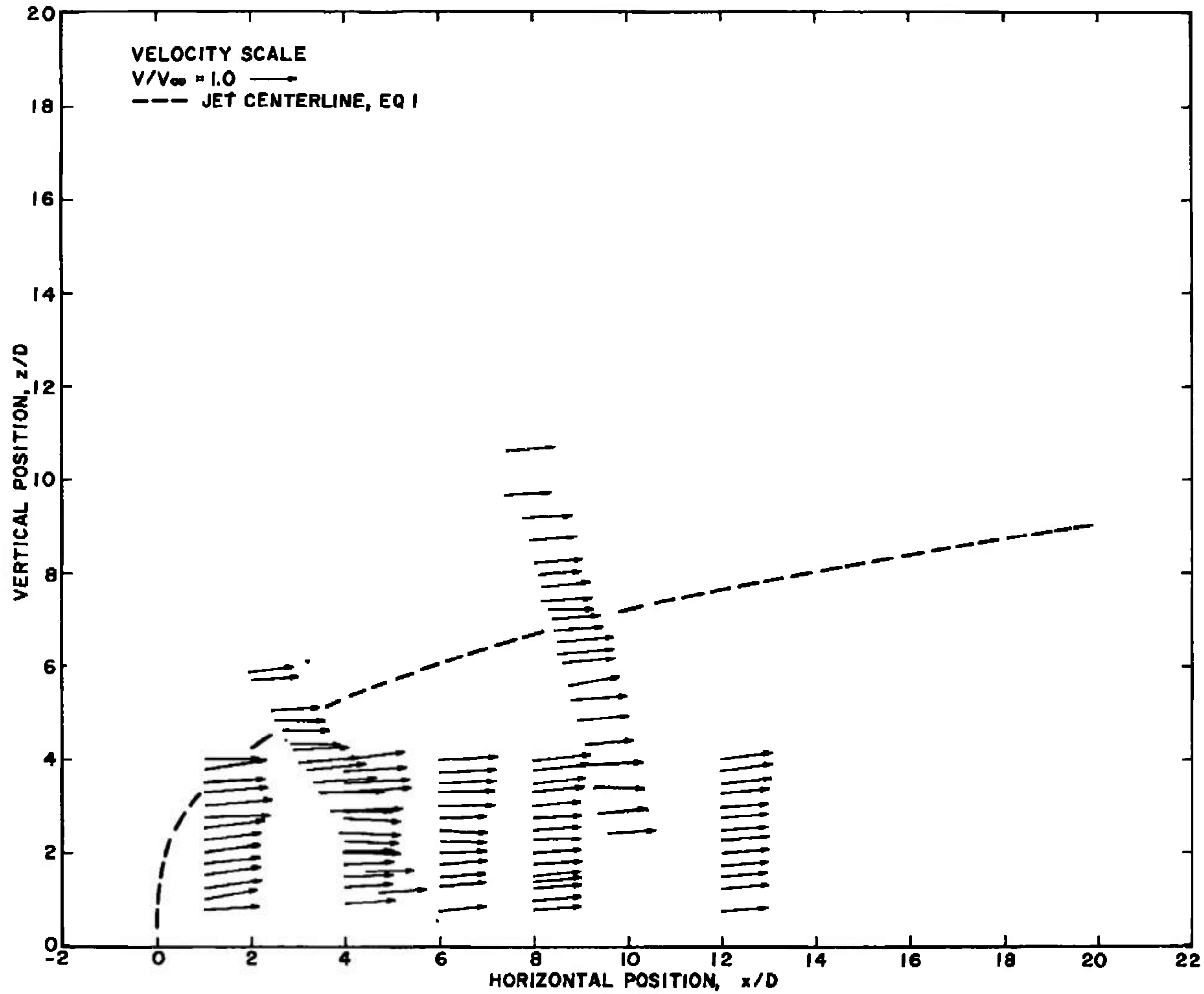
d. y/D = 4
Fig. 6 Concluded



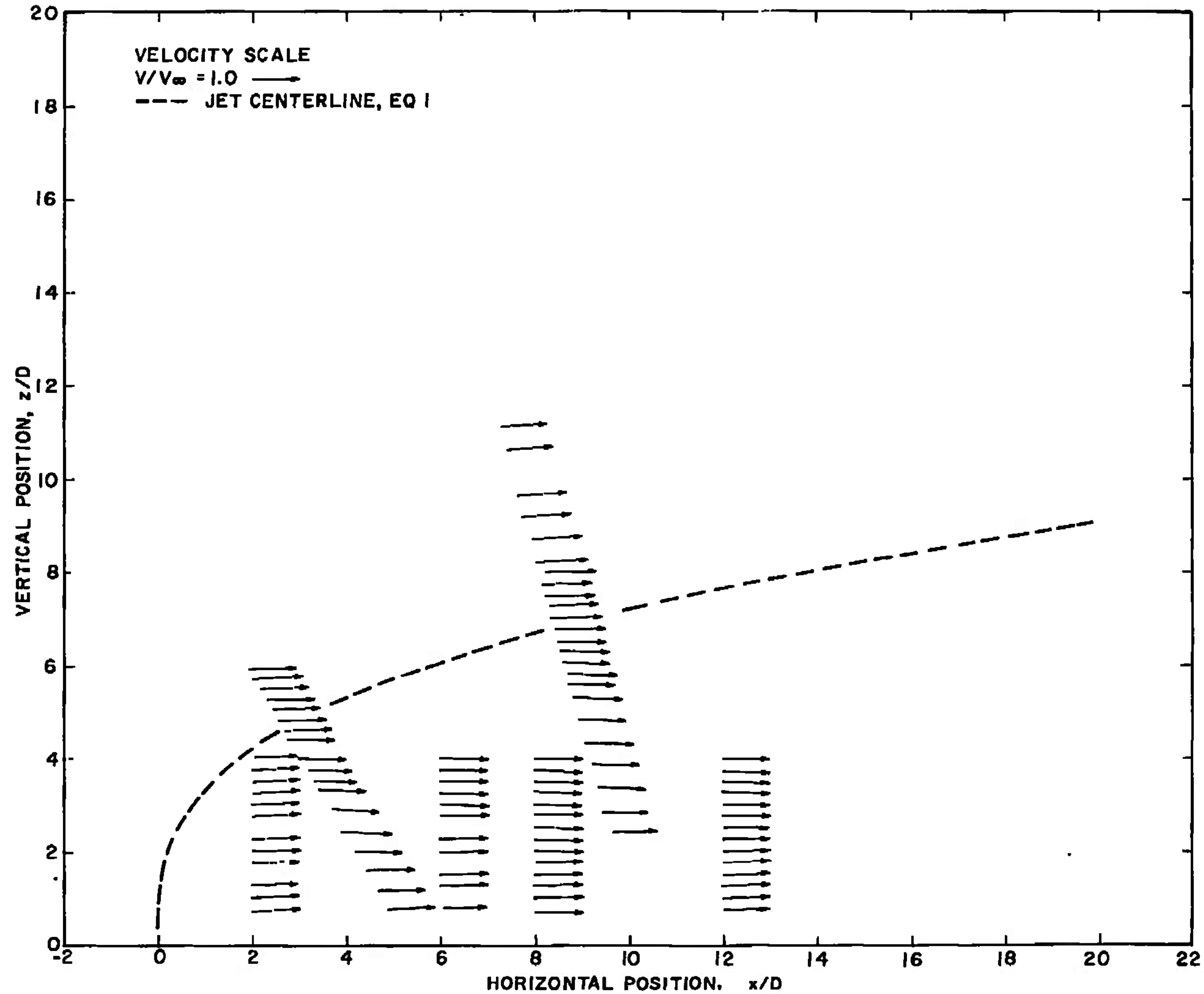
a. y/D = 0, Near Field
Fig. 7, Planar Velocity Field, V_e = 0.250



b. y/D = 0, Far Field
Fig. 7 Continued



c. y/D = 2
Fig. 7 Continued



d. y/D = 4
Fig. 7 Concluded

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13. ABSTRACT

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14. KEY WORDS	LINK A		LINK B		LINK C	
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measurements						
lasers						
velocimeters						
vertical takeoff aircraft						
wind tunnel tests						